


Docket No.: ZTP03P01879

CERTIFICATION

I, the below named translator, hereby declare that: my name and post office address are as stated below; that I am knowledgeable in the English and German languages, and that I believe that the attached text is a true and complete translation of PCT/EP2004/053374, filed with the European Patent Office on December 9, 2004.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Hollywood, Florida


Rebekka Pierre

June 9, 2006

Lerner Greenberg Stemer LLP
P.O. Box 2480
Hollywood, FL 33022-2480
Tel.: (954) 925-1100
Fax.: (954) 925-1101

IAP12 Rec'd PCT/PTO 09 JUN 2006

CONTROL FOR A BRUSHLESS DC MOTOR

[001] The present invention relates to a device and a method for controlling a brushless DC motor.

[002] A device of this type conventionally comprises an AC/DC inverter supplied by an intermediate direct voltage circuit for feeding stator windings of the DC motor and a pattern generator for controlling switches of the AC/DC inverter having a periodic switching signal pattern such that the stator windings in the motor generate a rotating magnetic field in the permanent magnets of the rotor attempt to align themselves. The torque which such a motor is capable of delivering depends on the angle between the permanent magnetic field of the rotor and the magnetic field of the stator windings in advance thereof. For optimal efficiency of the motor, the currents fed by the AC/DC inverter into the stator windings and the electromotive force (emf) induced therein by the turning of the rotor should be in phase. This means that the control voltage of the emf of the motor is more or less in advance. The lead angle at which the motor achieves the optimal efficient depends on the load of the motor, i.e., the torque exerted thereby and the speed. In order to operate the motor at the highest possible efficiency, load and speed are therefore normally measured and a lead angle known as optimal for a given combination of values of the load and speed (hereinafter calls the operating point of the motor) is set. The load is known to be proportional to the peak current of the individual stator windings which is why, to determine the load, the peak current is measured using an electronic peak value detector and the load is calculated therefrom.

[003] However, it is especially difficult to detect the peak current in cases of pulse-width-modulated control of the AC/DC inverter and low motor loads since, as a result of the small pulse widths, fast and therefore expensive comparators must be used in a peak value rectifier so that this can exactly reproduce the peak current at low pulse duty factors.

[004] It is the object of the present invention to provide a device and a method for controlling a brushless DC motor which allows the DC motor to be operated with high efficiency using simple and inexpensive means.

[005] The object is solved by a method having the features of claim 1 or a device having the features of claim 6.

[006] In contrast to the peak current strength, the average current strength can be detected exactly without any difficulties even at low loads but is not in any single-valued relationship to the motor load because the efficiency, that is the ratio of the product of load and speed to the consumed electrical power, depends on the lead angle. Nevertheless, this can surprisingly be used in an iterative method to adjust the operating point of a brushless DC motor.

[007] The desired value of the lead angle is preferably that value of the lead angle which maximises the efficiency of the motor for the allocated values of the speed and average power requirement. If the lead angle is approximated to this desired value, the resulting improvement in the efficiency of the motor for the same average power requirement of the motor results in an increase in the mechanical power, i.e. in an increase in the speed for the same load. By returning the speed to its desired value again by varying the average terminal voltage of the motor, the optimal operating point of

1 the motor for this desired speed is reached in the course of
2 several iterations.

3
4 [008] The desired value of the lead angle is preferably
5 determined using a characteristic map which specifies the
6 lead angle with the highest efficiency for a plurality of
7 operating points of the motor each defined by a speed and an
8 average power requirement. Such a characteristic map
9 generally specific for the design of the motor is preferably
10 first determined empirically and can be provided for the
11 control according to the invention in the form of a memory
12 module which gives the respectively optimal lead angle for
13 the various operating points.

14
15 [009] Since such a characteristic map can only comprise a
16 limited number of discrete operating points, in general the
17 load angle (lead angle) for an actual speed and average power
18 requirement is obtained from the characteristic map by
19 interpolation.

20
21 [010] In order to influence the average power requirement of
22 the motor, the average terminal voltage applied thereto is
23 preferably varied by pulse width modulation.

24
25 [011] A control device suitable for carrying out the method
26 comprises an AC/DC inverter for feeding the DC motor, a
27 pattern generator for controlling the switches of the AC/DC
28 inverter having a periodic switching signal pattern of
29 variable frequency and phase, which has an input for a
30 representative signal for an instantaneous phase position of
31 the rotor of the DC motor, wherein the pattern generator has
32 means for detecting the average current strength delivered by
33 the AC/DC inverter and means for adjusting a phase offset
34 between the phase position of the rotor and the switching

1 signal pattern depending on the detected average current
2 strength and the speed of the motor.

3
4 [012] In order to counteract any drift of the motor speed in
5 the event of a correction to the phase offset, means are
6 preferably provided for regulating an average terminal
7 voltage of the motor using a desired speed.

8
9 [013] The means for adjusting the phase offset preferably
10 comprise a phase-locked loop (PLL) circuit which can be
11 locked to the frequency of the input signal representative of
12 the phase position of the rotor. For adjusting the phase
13 offset control means are provided for predefining a target
14 phase offset depending on the detected power and speed of the
15 motor. These control means preferably include the afore-
16 mentioned storage device for the characteristic map, which
17 specifies for a plurality of operating points, respectively
18 one target phase offset which minimises the efficiency of the
19 motor.

20
21 [014] The speed of the motor can be detected using a speed
22 sensor coupled to the motor; preferably however the means for
23 adjusting the phase offset comprise means for deriving the
24 speed from the input signal representative for the phase
25 position of the rotor.

26
27 [015] The means for adjusting the phase offset can be divided
28 into a desired value transmitter which specifies a desired
29 value of the phase offset for the actual operating point and
30 generates a representative signal for this desired value and
31 a regulator for matching the actual phase offset to this
32 desired value using the representative signal. At the same
33 time, the representative signal can have values above and
34 below a representative value for a phase offset of 0° so that

1 standard processing of signals representative for positive
2 and negative phase offsets is possible in the regulator.
3

4 [016] Further features and advantages of the invention are
5 obtained from the following description of exemplary
6 embodiments with reference to the appended figures. In the
7 figures:
8

9 [017] Figure 1 is a block diagram of the control device
10 according to the invention and a brushless DC motor
11 controlled thereby;
12

13 [018] Figure 2 is a schematic circuit diagram of an AC/DC
14 inverter used in the control device in Fig. 1;
15

16 [019] Figure 3 shows the time sequence of the switching
17 states applied cyclically repeatedly to the motor; and
18

19 [020] Figure 4 is a diagram which illustrates the migration
20 of the operating point of a brushless DC motor controlled
21 using the device according to the invention.
22

23 [021] In the block diagram in Fig. 1, 1 designates a
24 brushless DC motor whose rotor has $n = 4$ pairs of poles. The
25 DC motor 1 is supplied by an AC/DC inverter 7 which is shown
26 in greater detail in Fig. 2. This comprises six switches SU1,
27 SV1, SW1, SU2, SV2, SW2 of which the switches SU1, SV1, SW1
28 are arranged between a positive supply terminal (+) and a
29 phase U, V or W of the motor 1 and the switches SU2, SV2, SW2
30 are each arranged between one of these three phases and a
31 negative supply terminal (-). The switches can be IGBTs known
32 per se with a suppressor diode connected in parallel.
33

[022] The switches of the AC/DC inverter are controlled by a control circuit 6 which applies six different switching states to the switches in a cyclically recurrent manner, these being explained in further detail with reference to Fig. 3.

[023] A Hall sensor 2 is located in the immediate vicinity of the rotor of the motor 1 to detect the field of each individual pole of the rotor which passes thereby. The Hall sensor 2 delivers an output signal which has an ascending flank in each case when passing a first type of pole and a descending flank when passing the other type of pole. The frequency f of the output signal of the Hall sensor 2 is thus n times the rotational frequency of the motor 1.

[024] The output signal of the Hall sensor 2 is applied to a first input of a phase comparator 3 whose second input is supplied with a comparison signal whose formation will be explained. The phase comparator 3 can be formed, for example, by an electronic counter which begins to count pulses of a clock signal whenever a descending signal flank arrives from the Hall sensor, the frequency of this signal being a multiple of the frequency f , until a descending signal flank is received at the second signal input and outputs the counter result as the measured value for a phase difference between the two signals.

[025] The output signal of the phase comparator 3 forms the non-inverted input signal of a differential amplifier 8 to whose inverting input is applied a representative desired-value signal provided by a microcontroller 21 for a desired phase offset between the pattern of the switching states and the output signal of the Hall sensor. The level of this desired-value signal is linearly relate to the desired lead

1 angle and can have values in a range whose limits should each
2 correspond to desired lead angles smaller or larger than 0° .
3 The lower limit preferably corresponds to a desired lead
4 angle of $-2\pi/3$ and the upper limit corresponds to a lead
5 angle of $+4\pi/3$ so values of the desired lead angle around 0°
6 can be adjusted by continuously varying the level of the
7 desired value signal.

8
9 [026] Connected to the output of the differential amplifier 8
10 is a proportional/integral controller consisting of a
11 weighting part 9 which multiplies the output signal of the
12 difference amplifier 8 with a pre-determined weighting
13 factor, and an integrator 10 for integrating the output
14 signal of the differential amplifier. The additively
15 superposed output signals from the weighting part 9 and
16 integrator 10 are fed to a voltage-controlled oscillator 5 as
17 a frequency-controlled signal together with further
18 contributions added in an adder 11.

19
20 [027] In addition to the phase comparator 3, a period
21 measuring circuit 12 is connected to the output of the Hall
22 sensor 2, which circuit measures the time between two
23 successive descending flanks of the signal from the Hall
24 sensor 2 and delivers this as an output signal to an average
25 value circuit 13 and a first shift register 14. Connected to
26 the output of the first shift register is an input of a
27 second shift register 15 and a second input of the average
28 value circuit 13; connected to the output of the second shift
29 register is a third shift register 16 and a third input of
30 the average value circuit 13, and at the output of the third
31 shift register a fourth input of the average value circuit
32 13. With each new period measured value supplied by the
33 measuring circuit 12, this triggers the shift registers 14,
34 15, 16 so that these take over and output the measured value

1 respectively applied to their input. Thus, the four most
2 recent measured values of period durations of the Hall sensor
3 signal are always applied to the inputs of the average value
4 circuit 13. The average value circuit 13 delivers the average
5 of these measured values at its output. (In general, if the
6 number of pairs of rotors is n , n inputs and $n - 1$ shift
7 registers are always provided so that averaging is performed
8 over the number of periods of the Hall sensor signal which
9 corresponds to a complete revolution of the rotor). Cyclic
10 fluctuations in the period duration which can result from
11 non-uniformities in the arrangement of the four pairs of
12 poles of the rotor are thus eliminated in the output signal
13 of the average value circuit 13. This output signal makes a
14 substantial contribution to the input voltage of the voltage-
15 controlled oscillator 5. Thus, after two passages of the
16 rotor through the reference position, an input voltage is
17 applied to the oscillator 5 which is not far removed from the
18 input voltage which would be established in the steady-state
19 mode and the frequency of the oscillator 5 can rapidly lock
20 to that of the rotor.

21
22 [028] The output of the average value circuit 13 is further
23 connected to a difference circuit 18, on the one hand
24 directly and on the other hand via a fourth shift register 17
25 which is triggered in a similar manner to the shift registers
26 14 to 16 so that the difference circuit 18 delivers the
27 difference between two successive averaged periods of the
28 Hall sensor signal as an output signal. The output signal of
29 the difference circuit 18 thus corresponds to the average
30 variation of the period duration and indicates an accelerated
31 or slowed running of the motor 1. This accelerated or slowed
32 running is taken into account by adding the output signal of
33 the difference circuit 18, weighted by a factor of 0.5 in a
34 weighting part 19, to the afore-mentioned contributions to

the input signal of the oscillator 5 in the adder. Thus, the oscillation of the oscillator 5 already allows for a variation of the period duration which is to be expected in extrapolation of the past but has not yet been measured.

[029] The voltage-controlled oscillator 5 delivers an oscillation whose frequency in the steady-state mode is six times as high as that of the Hall sensor signal. A 1/6 count-down oscillator 20 produces the comparison signal supplied to the phase comparator 3 herefrom. The control circuit 6 receives the output signal with the frequency $6f$ from the voltage-controlled oscillator 5 and derives the control signals for the switches of the AC/DC inverter 7 from this. In the time diagram in Fig. 3 the oscillation of the voltage-controlled oscillator 5 is designated by VCO. The control circuit 6 responds to its ascending flank by changing from one of six cyclically successively produced switching states a, b, c, d, e, f to the next.

[030] For each of the switching states a to f Figure 3 shows the state of the switch of the AC/DC inverter 7 and the voltages resulting therefrom at the phases U, V, W of the electric motor 1. In state a the switches SU1, SW1 are closed. The switches SU2, SW2, SV1 are open and the switch SV2 is opened and closed in pulsed mode, the pulse duty factor being specified by a power control signal which the control circuit 6 receives from the microcontroller 21. According to the pulse duty factor of the switch SV2, current flows through the phases U, V or W, v of the motor and the resulting magnetic fields are superposed to form a space vector u_a . In the following switching state b, the switches SV2, SW2 are open, SU2, SV1, SW1 are closed and SU1 is pulse-width-modulated with a pulse duty factor specified by the power control signal of the microcontroller 21; accordingly

current flows through the phases U, V and U, W and results in a space vector u_b which is turned through 60° in the anticlockwise direction compared with u_a . The closed, open, pulse-width-modulated, states of the switches for states c, d, e, f and the resulting current distributions and space vectors can be read off from Fig. 3 and do not need to be explained here in detail. It is important that six periods of the VCO signal produce a rotation of the space vector through 360° .

[031] Naturally, the states of the AC/DC inverter 7 controlled by the control circuit 6 can be different from those shown in Fig. 3, in particular, although less preferred, a state pattern can be considered where each phase U, V, W of the motor 1 is kept current-free for the length of respectively one state by opening both allocated switches, then connected to the positive supply voltage for the length of two states, then kept current-free for the length of one state again and finally connected to the negative supply terminal for the length of two states and the three phases are phase-shifted with respect to one another by respectively two states.

[032] The efficiency of the electric motor 1 depends on the lead angle between the magnetic field generated by the windings of its state and the rotor rotating in this field. For each operating point characterised by a speed and a torque or in an equivalent manner, by a speed and a mechanical power, there is an optimal lead angle which can be determined empirically, for example, for a specific motor model. Since, as has already been explained, the determination of the peak current from which the load (the torque) could be uniquely calculated, is complex, a different approach is selected in the control device according to the

1 invention. In this case, the microcontroller 21 detects the
2 electrical power requirement of the motor 1, for example, as
3 shown in Fig. 1, using a series resistor 22 disposed in the
4 intermediate circuit of the AC/DC inverter 7 to which a
5 voltage proportional to the current strength of the
6 intermediate circuit is applied. If the intermediate-circuit
7 voltage is assumed to be constant, measurement of this
8 current strength is sufficient to determine the electrical
9 power requirement; on the other hand, it can be provided that
10 the microcontroller 21 also measures the intermediate-circuit
11 voltage and calculates the power requirement as a product of
12 intermediate circuit voltage and current strength. The speed
13 of the motor 1 is determined by the micro-controller 21 from
14 the output signal of the adder 11 which is proportional
15 hereto.

16
17 [033] A characteristic map which gives the optimal lead angle
18 for a set of operating points is stored in a memory module 23
19 connected to the microcontroller 21. This set of operating
20 points is selected in a manner known per se so that for all
21 practically relevant operating points of the motor 1 not
22 contained therein, the respectively optimal lead angle can be
23 calculated by interpolation in the microcontroller 21.

24
25 [034] The operating mode of the microcontroller is explained
26 with reference to Fig. 4. The figure is a three-dimensional
27 diagram in which a curved surface K represents the
28 relationship between speed U , mechanical power P and optimal
29 lead angle θ stored in the characteristic map. A point P_0 in
30 this diagram represents an arbitrary starting point of the
31 regulating method executed by the microcontroller 21. This is
32 characterised by a value of the speed deduced by the
33 microcontroller from the output signal of the adder 11, an
34 (arbitrary) lead angle θ which the microcontroller 21 applies

1 as the desired value to the differential amplifier 8, and a
2 mechanical power P of the motor which the microcontroller 21
3 estimates from the consumed electrical power by multiplying
4 with a known efficiency η of the motor. The efficiency η is
5 that efficiency achieved by the motor at the given speed with
6 an optimally adjusted lead angle θ . At the point P_0 the lead
7 angle is higher than the optimal value so that the mechanical
8 power of the motor is actually lower than the value estimated
9 by the microcontroller 21. However, this is not disturbing
10 for the purposes of the method. Using the values of the speed
11 and mechanical power thus obtained the microcontroller 21
12 determines the optimal lead angle corresponding to the
13 operating point using the characteristic map K (where it
14 imputes the estimated value of the mechanical power to be the
15 true value) and predefines the lead angle thus determined as
16 the desired value to the differential amplifier 8. Thus, the
17 point P_1 is in the diagram in Fig. 4 is reached.

18
19 [035] Since the mechanical power of the motor assumed by the
20 microcontroller is based on an approximation, in reality no
21 point is reached on the surface K but the efficiency of the
22 motor 1 is improved by correcting the lead angle.

23 Consequently, the speed and/or mechanical power of the motor
24 increase and the estimated operating point migrates towards
25 P_2 . The microcontroller 21 now recognises that the desired
26 speed is exceeded and the control circuit 6 reduces the pulse
27 duty factor preset by the afore-mentioned power control
28 signal. If the lead angle remains the same, the speed and/or
29 power decrease again and the point P_3 is reached. At this
30 point, as previously at point P_0 , the optimal lead angle is
31 estimated from the characteristic map and set for the assumed
32 operating point. The procedure is repeated iteratively until
33 it finally converges to the point P where the lead angle θ is

1 optimally adjusted and the efficiency of the motor is
2 actually equal to θ .
3 [036]
4